DISCUSSION.

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The results of pilot balloon observations at San Juan are of great interest, since they constitute a fund of information concerning free-air conditions in a region in which little work of the kind has heretofore been carried on. Their value is great or small in proportion as they can be shown to be truly representative of actual conditions. Aside from the usual limitations to which observations with balloons are subject, viz, absence of clouds in the lower levels, good visibility, and moderate wind speeds, there is in the present case the added uncertainty as to the conformity of the actual rate of ascent to the assumed rate.

Theoretically we should expect a balloon to rise at a rate inversely proportional to the sixth root of the density.[1] For summer time conditions in this country,

[1] Cave, C. J. P.: The structure of the atmosphere in clear weather, p. 4, 1912.

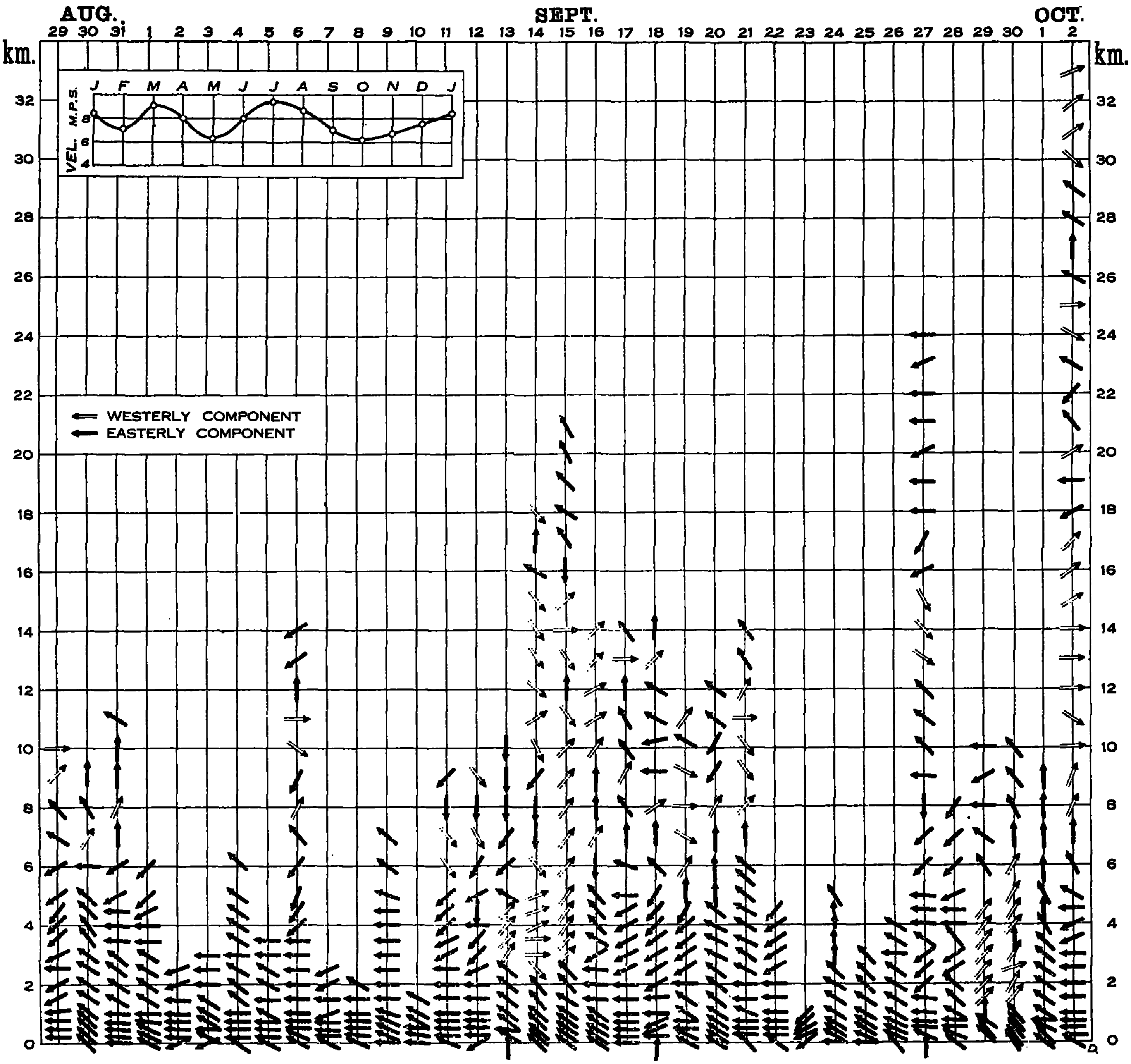

FIG. 1.—Wind direction at various elevations at San Juan, P. R., Aug. 29–Oct. 2, 1923. Inset: Average wind velocity for each month from surface to highest elevation attained at San Juan, P. R., January to May, inclusive, and December based on one year's observations, June on 3 years, and remaining months on 4 years.

approximately those prevailing at San Juan, this would give the following average rates of ascent, calling that at the surface unity:

Altitude.	Density.	Rate of ascent.
km.	*g/m.*³	
0	1.175	1.000
5	.723	1.084
10	.418	1.188
15	.209	1.333
20	.095	1.521
25	.048	1.704
30	.023	1.926

Observations with two theodolites show that there is no such increase in the ascensional rate but that instead the rate is essentially constant, owing in large part presumably to the counteracting influence of diffusion through the rubber envelope. We do not know the extent of this diffusion as the balloon rises, but with a balloon inflated for an ascent the rate has been found to be about 4 to 6 per cent of the volume per hour,[2] with little change in the rate during the first 4 hours.[3]

Computation for an average weight balloon, inflated to ascend at 180 m./min., the rate of diffusion being assumed as 6 per cent, gives 227 m./min. as the ascensional rate at 15 kilometers, or 1.261 times the initial rate as against 1.333 shown in the table. Evidently, then diffusion increases rapidly as the balloon expands, though there may be other influences tending to produce a de-

[2] Sherry, B. J., and Waterman, A. T.: The military meteorological service in the United States during the war. MO. WEATHER REV., April, 1919. 47: 219.

[3] Johnson, N. K.: The behavior of pilot balloons at great heights. *Quar. Jour. Roy. Met. Soc.*, 48: 53. 1922.

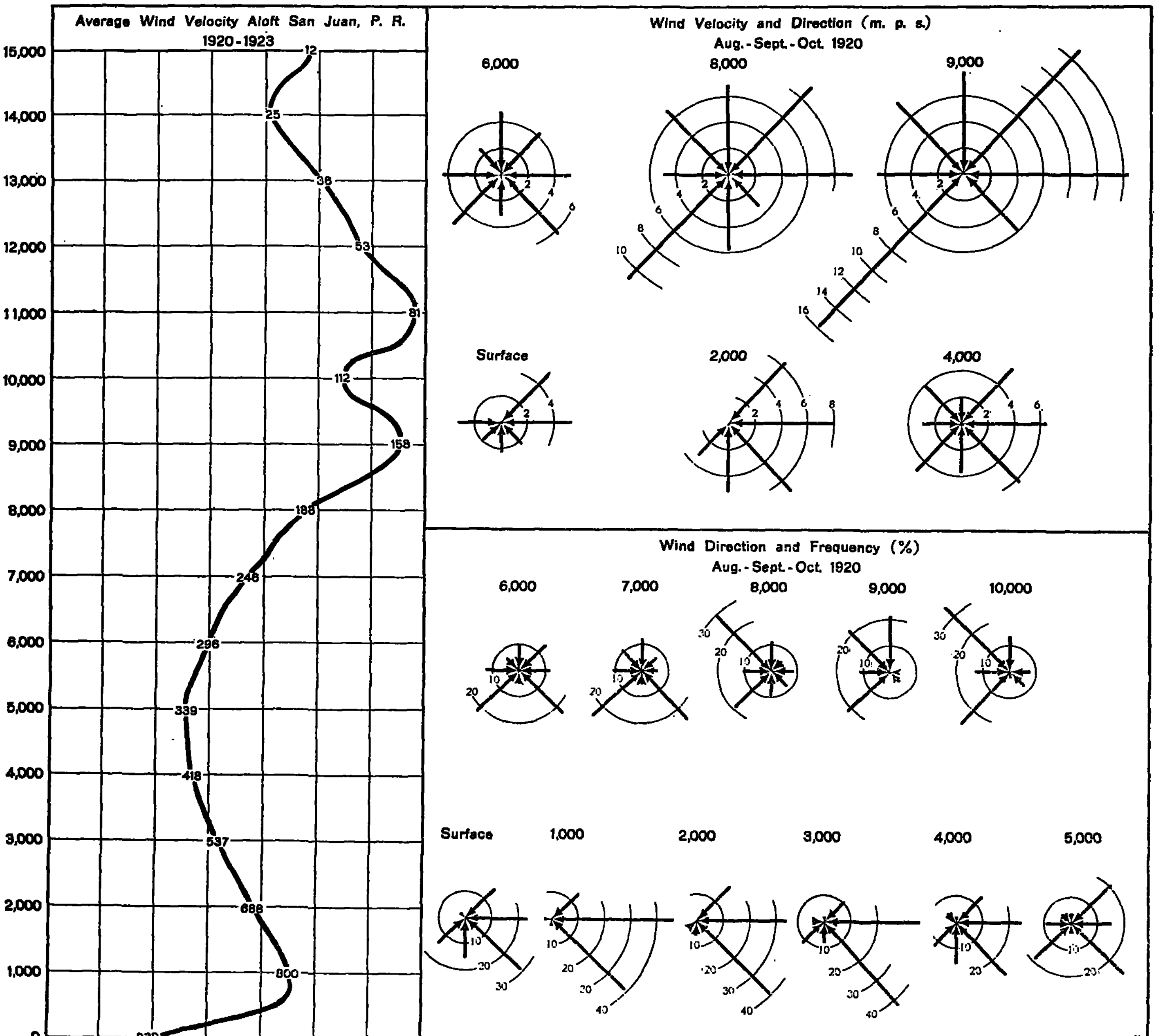

FIG. 2.—Left: Average wind velocity, surface to 15 kilometers, at San Juan, P. R., 1920-1923. (Number of observations upon which average is based indicated along the curve.) Upper right: Average wind velocity and direction at several elevations for autumn, 1920, at San Juan, P. R. Lower right: Percentage frequency of winds from different directions, autumn, 1920, San Juan, P. R.

creased rate, such as the effect of low temperatures on the elasticity of the rubber. The only way in which these factors could be evaluated would be to place a balloon in an altitude chamber and subject it to pressure and temperature conditions similar to those through which it passes during actual ascents. Even then only a rough approximation could probably be realized.

In the absence of such tests it has been necessary to resort to the results of double theodolite observations. This was done during the war by the officers of the United States Signal Corps,[4] and the following empirical formula was developed, in which V is the rate of ascent in m./min., 1 is the free lift or ascensional force in grams and L is the free lift plus the weight of the balloon:

$$V = 71\left(\frac{l^3}{L^2}\right)^{.208}.$$

	1	2	3	4	5	6	7	8	9	10
Assumed	216	198	198	189	189	180	180	180	180	180
a. m. (292)	204	185	181	181	182	181	180	183	180	181
p. m. (513)	222	206	204	197	191	185	184	182	183	183
a. m. and p. m. combined (805)	216	197	196	190	187	184	182	182	182	181

The a. m. observations are ordinarily taken between 7 and 8, and the p. m. between 3 and 4. Figures in brackets give the number of observations on which the means are based.

The mean rates for all observations show striking agreement with those assumed. It is evident, though, that in the morning hours before convection sets in no additive corrections are necessary except in the first minute, whereas in the afternoon somewhat larger corrections are needed than those that have been adopted. After the fifth minute, i. e., above 1 kilometer, both a. m. and

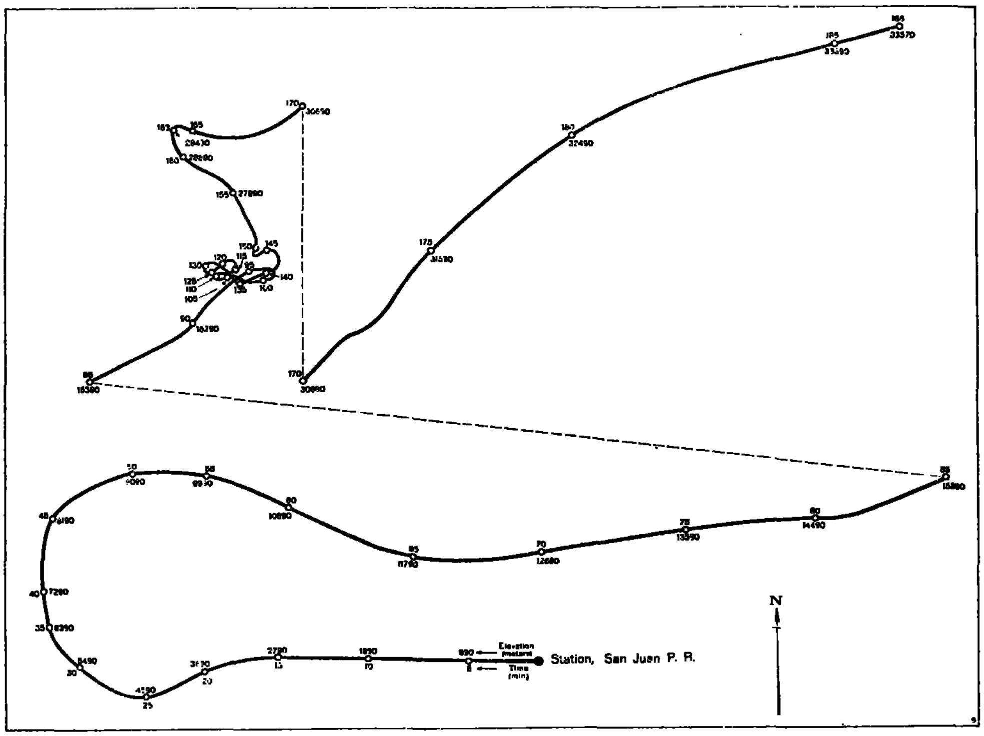

FIG. 3.—Horizontal trajectory of pilot balloon flight of October 2, 1923. Time in minutes and elevation of balloon in meters indicated along the curve.

p. m. rates are in good accord. The figures are of course averages. Inspection of the individual observations shows that the actual altitude at the end of 10 minutes was within 10 per cent of the assumed in 99 per cent of the morning runs, 64 per cent of the afternoon, and 75 per cent when all are combined. Most of the larger variations occurred when convection was active and therefore when wind speeds were low and the resulting error of comparatively little consequence. Convection is the principal source of error in these lower levels, but it seldom extends above 2 kilometers except on hot summer afternoons. Whatever error it introduces is therefore a constant in the higher levels and the percentage of error from this cause diminishes with height.

Above 1 to 2 kilometers we have then to deal principally with the behavior of balloons in still air (i. e., "still" in a vertical sense). The 805 observations that have been considered extended to various heights above 2 kilometers, some 50 of them reaching 10 to 15½ kilo-

This formula was based upon about 1,000 observations. After the war a slight revision was made as the result of further study and the inclusion of additional data secured by the Weather Bureau and the Signal Corps. The revision consisted of a change in the constant from 71 to 72 and of the introduction of small additive corrections for the first five minutes of ascent.[5] All single theodolite observations made in this country, including those at San Juan, since April 1, 1921, have been computed by this revised formula.

During this latter period observations with two theodolites have been continued, more than 800 having been made in which the balloon was followed by both theodolites for 10 minutes or longer. The following tabulation gives the assumed and the average computed rates in m./min. for each of the first 10 minutes:

[4] Sherry, B. J., and Waterman, A. T.: *Loc. cit.*, p. 218.
[5] Sherry, B. J.: The rate of ascent of pilot balloons. MO. WEATHER REV., December, 1920. 48: 692-694.

meters. Almost without exception the ascensional rates between 2 and about 10 kilometers were essentially constant. Above 10 kilometers, however, there is evidence of an increase in the rate. A typical, and also thus far the highest, observation is shown in figure 4, in which the broken curve represents the time-altitude relation in a double theodolite run at Groesbeck, Tex., on the afternoon of August 24, 1923, and the straight line gives the assumed rate. Up to 10 kilometers the two lie close together, but above that height there is a gradual falling apart. Even so, the error at the greatest height reached is not quite 5 per cent, the actual height being 15,360 meters as against an assumed value of 14,670. Whether or not this departure from a constant rate continues or perhaps increases at greater heights is not known.

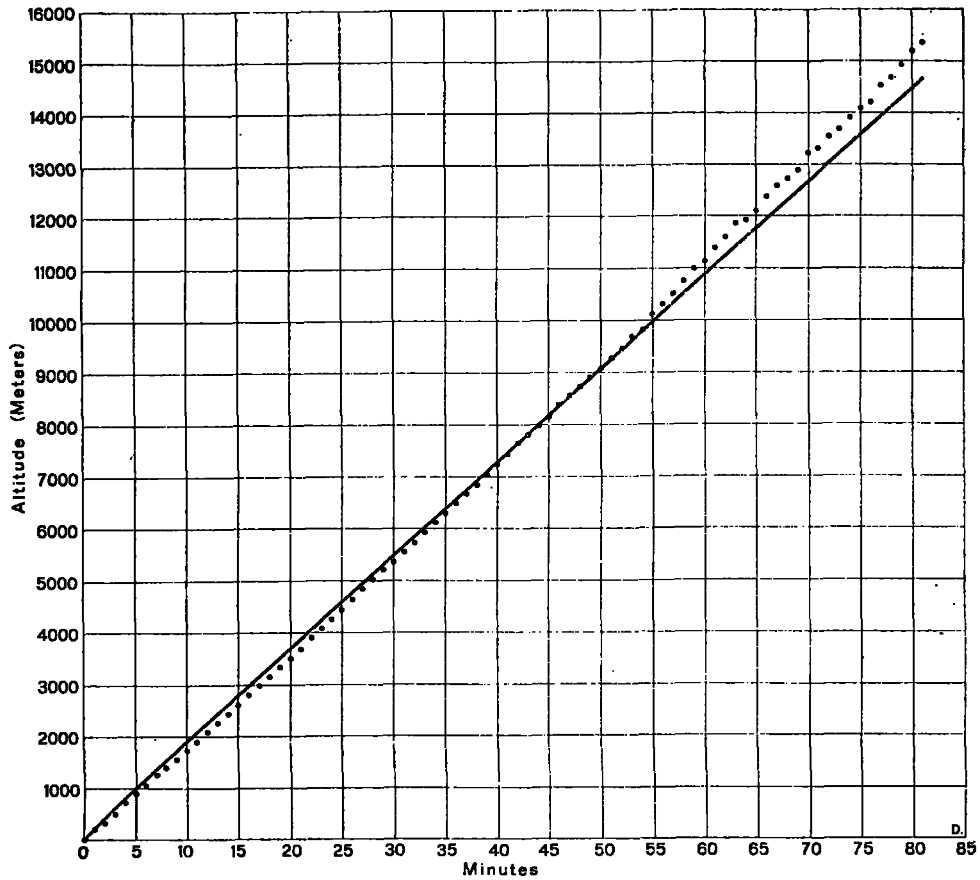

FIG. 4.—Time-altitude graph of highest double-theodolite pilot-balloon observation at Groesbeck, Tex., August 24, 1923.

Efforts are being made, whenever opportunity offers, to obtain double theodolite observations to as great heights as possible and it is hoped that more light on this question will soon be available.

It is worthy of note that of the 805 cases examined only one, or possibly two, showed evidence of a slow leak caused by pinholes. Not a single case was found in which the balloon reached a state of equilibruim and floated. As a rule observations ended because of the bursting of the balloons or disappearance on account of distance, haziness or clouds.

CONCLUSIONS.

1. On the average there is striking agreement between the assumed and the actual heights at all levels from the surface to about 10 kilometers.

2. In individual observations the actual heights at the end of 10 minutes, about 2 kilometers, are within 10 per cent of the assumed in about three-fourths of all cases, the largest departures occurring when convection is active and therefore when horizontal air movement is slight and the error of small consequence. Observations taken in the morning hours are correct within 10 per cent in practically *all* cases.

3. At heights between 2 and about 10 kilometers the accuracy is still greater, since convection is ordinarily absent at these levels and the balloons ascend at essentially a constant rate, very close as a rule to the assumed rate.

4. From 10 to 16 kilometers the rate increases gradually and assumed heights are 5 to 10 per cent too small at 14 to 16 kilometers.

5. As to what takes place above 16 kilometers we have at present no information. It seems likely, though, that the best balloons continue to rise to perhaps 20 or 25 kilometers, and that the rate of ascent increases considerably.

6. So far as observations at San Juan are concerned, it seems reasonable to conclude: (*a*) That mean values are essentially correct; (*b*) that individual observations, since they are made in the morning hours, are correct within 10 per cent in the lower levels and within 5 to 10 per cent at heights between 2 and 15 kilometers; and (*c*) that at heights above 15 to 16 kilometers nothing definite can be stated at present as to their dependability.

A more detailed study of the general problem of behavior of pilot balloons is in preparation.